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DOCUMENT-IDENTIFIER: US 6161435 A
TITLE: Method and apparatus for determining the state of fouling/cleaning of membrane modules

Abstract Text (1):
The fouling state of a polymeric membrane within the high pressure housing of a spiral wound or a hollow fiber membrane module is determined. An ultra sonic transducer positioned with its emitting face in physical engagement with the outer surface of the housing is pulse energized by a pulser/receiver device. A membrane echo signal is detected by a receiver of the pulser/receiver device. A reference echo signal indicative of a fouled or an unfouled state of the membrane is compared to the echo signal to determine the membrane fouling state. The echo to reference comparing step can be based upon comparing amplitude domain signals, comparing time-domain signals, comparing combinations of amplitude domain and time-domain signals, and comparing transformations of amplitude domain and time-domain signals. A clean or a fouled reference echo can be provided from a clean or a fouled membrane and then stored for use during a liquid separation process, or a clean reference echo signal can be obtained on-line from a second transducer whose echo signal is derived from an area of the membrane known to remain relatively unfouled during the liquid separation process, or a clean or fouled reference echo signal can be provided for later use during a cleaning process or during a liquid separation process. Multiple transducers and a switching network can sample the fouling state at different positions within the membrane module.

Brief Summary Text (8):
Measurement of the fouling and/or cleaning of membranes that are used in liquid separation processes is pivotal to the art if membranes are to be widely used. The lack of suitable techniques for studying membrane fouling under realistic operating conditions has hindered the development of strategies to improve resistance to fouling. Moreover, although a decline in the permeate flow rate (i.e., the treated liquid flow rate) can be used to infer that membrane fouling is occurring, or has occurred, flow rate measurement does not provide a determination of when a membrane module has been adequately cleaned via chemical means, back flushing, or any other cleaning means, since permeation flow does not occur during membrane cleaning, and flow rate measurements are not made during cleaning.

Brief Summary Text (9):
It is known that the fouling of membrane modules can be detected by means of an optical probe. However, use of an optical probe requires that an optical window be formed in a wall of the housing that internally holds the membrane. This procedure is not practical in commercial high-pressure membrane modules. Moreover, optical probes provide information on membrane fouling relative to only on the outermost portion of the membrane. That is, interior membrane portions cannot be seen via an optical probe.

Brief Summary Text (10):
It is also known that an indirect measurement of membrane fouling can be obtained via measurement of the permeate flow rate out of the membrane, an increase in back pressure, or via measurements of the output permeate's composition. Membrane fouling is known to cause a decline in the permeate flow rate. However, permeate

flow rates can decline for reasons other than membrane fouling. For example, concentration polarization and membrane compaction also causes the permeate flow rate to decline. Moreover, permeate flow rate measurements cannot be used to assess the effectiveness of cleaning fouled membrane surfaces, since normal permeate flow measurement does not occur during membrane cleaning.

Brief Summary Text (11):
The same criticisms apply to using an analysis of the permeate composition to assess membrane fouling. In particular, permeate composition does not provide appropriate information during the cleaning of fouled membrane modules, since feed composition changes occur during cleaning.

Brief Summary Text (12):
Membrane fouling has been identified as the major factor that limits the implementation of membranes in liquid separation processes. Moreover, membrane fouling limits the time period during which a membrane module can be used before a need to clean the membrane module arises.

Brief Summary Text (13):
It is known that others have used ultrasonic time-domain reflectometry when studying membrane formation and membrane processes. This prior work has involved studies of membrane formation, membrane compaction, membrane fouling, and defect formation in membranes. However, this aforementioned work has not included an apparatus, meter or method for measuring membrane fouling and/or membrane cleaning in membrane modules, such as spiral wound and hollow fiber membrane modules. For example, see an article entit~~led Real-Time~~ Nondestructive Characterization of Membrane Compaction and Fouling, REVIEW OF PROGRESS IN QUANTITATIVE NONDESTRUCTIVE TESTING, Vol. 14, Plenum Press, 1995, pages 1167-1173, that describes how compaction and fouling were characterized in-situ, and in real-time, using a nondestructive ultrasonic technique relative to a thin film membrane whose structure consisted of a 0.2 micro-meter thick polyamide layer supported by a 40 micro-meter thick polysulfone substrate attached to a 150 micro-meter thick polyester web.

Brief Summary Text (15):
The present invention satisfies a need in the art for an apparatus/method for detecting the initiation of membrane fouling as well as the state of membrane fouling and the rate of membrane fouling, to thereby provide an early warning that permits adjusting system operating parameters to mitigate the fouling problem.

Brief Summary Text (16):
By providing a measurement of membrane fouling, the present invention satisfies a need in the art for an apparatus/method that determines when a membrane module should be cleaned, as contrasted to techniques that provide measurements that might be a result of factors other than membrane fouling, such as membrane compaction.

Brief Summary Text (21):
The present invention provides a fouling meter that operates to monitor membrane fouling and/or membrane cleaning within a membrane module, online, in real time, and noninvasively.

Brief Summary Text (24):
The present invention employs ultrasonic or Acoustic Time-Domain Reflectometry (ATDR) to detect membrane fouling noninvasively, in real-time, and the invention operates to detect membrane fouling on an internal portion or portions of a membrane that is housed within a rigid metal, plastic, or metal/plastic housing. Moreover, this invention does not require that any type of window be cut in the housing to permit detecting the fouling of a membrane that is within a membrane housing. This invention also distinguishes between membrane fouling and changes that might result from concentration polarization or membrane compaction.

Brief Summary Text (25):
A particular advantage of this invention is that the apparatus/method of the invention can be used to assess the degree of membrane fouling during cleaning of the membrane, and therefore the invention can be used to terminate the costly cleaning process when operation of the invention determines that a membrane module has been satisfactorily cleaned.

Brief Summary Text (32):
Now assume that membrane fouling occurs; i.e., that fouling layer 20 exists. As a result, a dotted line echo signal 28 is provided by the interface that is formed by the bottom surface of the liquid that is within area 15 and the top surface 18 of the membrane layer/fouling layer area 12.

Brief Summary Text (35):
The principles above described relative to FIGS. 1 and 2 are used in the operation of the present invention, wherein the fouling of a membrane operates to change both the distance between the membrane/solution interface and the transducer (the distance change depending upon the thickness of the fouling material) and the acoustic impedance of the membrane/solution interface. As an example, increased thickening of layer 12 causes echo pulse 27 to move to the left in FIG. 2, and compaction of membrane 19 causes echo pulse 27 to move to the right in FIG. 2. In some cases, membrane fouling will not result in an appreciable change in the distance between the membrane/solution interface and the transducer.

Brief Summary Text (36):
The present invention provides a unique in situ and noninvasive method/apparatus that quantifies the fouling of a spiral wound or a hollow fiber membrane, in real-time, using acoustic time domain reflectometry. This invention also has utility in determining membrane fouling/cleaning in membrane based liquid separation systems (i.e., microfiltration systems, ultrafiltration systems, nanofiltration systems, and reverse osmosis filtration systems).

Brief Summary Text (37):
A valuable utility of this invention provides a membrane fouling meter or device for the noninvasive and real time measurement of membrane fouling/cleaning. Such a fouling meter has utility in determining the optimal time for which a membrane module should be cleaned. Moreover, this fouling meter facilitates determining when the membrane module has been adequately cleaned. In addition, this fouling meter has utility in assessing the effectiveness of new techniques that are developed to control and mitigate membrane fouling.

Brief Summary Text (38):
This invention adapts the ATDR technology to the measurement of membrane fouling and membrane cleaning in membrane modules that employ multi-layer membrane elements, such as spiral wound and hollow fiber membrane elements.

Brief Summary Text (44):
This invention relates to the use of an ATDR technology to measure membrane fouling, and to measure the efficiency of membrane cleaning, in Reverse Osmosis (RO) membrane module system employing both spiral wound and hollow fiber membranes, one example being a RO system that used Filmed SW30-2521 spiral-wound membrane modules, and another example being a hollow fiber membrane module by Akzo-Nobel.

Brief Summary Text (50):
In the development of this invention, a replication of calcium sulfate fouling and cleaning studies using spiral-wound membrane modules supplied by Fluid Systems were performed wherein A-scan and B-scan measurements were made along the axis of the spiral-wound membrane in order to assess module geometric and flow effects on membrane fouling. The ATDR signals from each successive spiral-wound membrane layer

were isolated, or a complete response from many membrane layers was used, and a determination was made relative to the influence of system operating parameters including pressure on ATDR measurements.

Brief Summary Text (51):
In an embodiment of this invention, ATDR studies of membrane fouling and membrane cleaning efficiency were made using #2521 spiral-wound membrane modules supplied by Filmtec. Typical operating conditions were 225 psi, 22 C, feed concentration of 820 mg/l of CaSO.sub.4, and a running time of approximately 95 hours. FIG. 9 shows an ATDR signal trace that was obtained during the cleaning of a spiral-wound membrane module.

Brief Summary Text (60):
Quantitative Data: Current techniques permit determining membrane fouling only via indirect measurements of quantities, such as the permeation flow rate. Flow rate can change due to factors other than membrane fouling; for example, concentration polarization and membrane compaction. Permeate flow rate provides only a measure of the permeate flux integrated throughout the entire module rather than being a local measurement; whereas fouling can be a localized phenomenon owing to the influence of module hydrodynamics that vary along the module. Moreover, permeate flow rate can be measured only when a module is in operation; as such, flow rate provides no information during membrane cleaning. The present invention, employing ultrasonic time domain reflectometry, provides local measurement of membrane fouling. As such, the invention can be used to scan across the bulk of a membrane module, to thereby permit improved module design and/or module operating conditions. This apparatus/method of this invention can also be used at any time that the module is liquid filled. Hence, this invention can be used to provide information on membrane fouling both during operation and during cleaning.

Brief Summary Text (61):
Simplicity: The present invention utilizes an ultrasound technology, the elements of which have been successfully applied to both nondestructive testing and a wide range of process measurement applications. This invention provides a simple technique for the direct measurement of membrane fouling. By comparing the reflection or echo signal (or the complete response from a series of membrane layers) that results from operation of this invention, either during operation or during cleaning, with a calibration reflection signal that defines a clean membrane, it is possible to assess both the presence of, and the degree of, membrane fouling. An embodiment of this invention employs transducers that are fixed in position and do not require mechanical scanning.

Brief Summary Text (62):
Ease of Application: This invention can be retrofitted onto many current membrane modules, and can also be integrated into newly-manufactured membrane modules. The invention does not require a housing window to access the interior of the membrane module. An embodiment of the invention employs a stand-alone unit that can be removed from one membrane module, and installed on another membrane module.

Brief Summary Text (63):
Versatility: This invention can be applied to modules having either a spiral-wound or a hollow fiber membrane, as well as to other types of membranes. This invention operates to detect the presence of membrane fouling that occurs due to suspended particulates, as well as inorganic, organic, and biological precipitates.

Brief Summary Text (64):
Image Data: A modified form of this invention employs scanning to thereby image local membrane fouling that may be localized within the bulk of a membrane, in contrast to other techniques that only provide data relative to the entire membrane.

Detailed Description Text (2):
One aspect of the present invention provides an apparatus/method for measuring the fouling of pressure driven membrane modules; for example, membrane modules that contain either a spiral-wound membrane or a plurality of hollow fiber membranes. The invention provides for a measurement of the buildup of particulates and/or precipitates on a membrane that is contained within the housing of a membrane module. In a new and unusual manner, this invention employs an ultrasonic measurement system that employs high frequency sound waves to detect the presence of membrane fouling/cleaning in a noninvasive and real-time manner.

Detailed Description Text (5):
The transducer is now pulse energized, to preferably produce a transmit-receive or pulse echo mode of operation. A time-domain membrane reflection or echo signal or multi-layer response is recorded. Comparison of this reflection signal to a standard or reference enables a determination to be made as to the state of membrane fouling/cleaning.

Detailed Description Text (25):
The amplitude and/or the arrival time of the reflected signals that are received from membrane layers that are deeper within the membrane also change as membrane fouling develops. The nature of the amplitude/arrival time change is dependent upon the reflection and scattering that occurs at the membrane layers that are closer to the ultrasonic transducer. Also, the characteristics of the fouling signal that is received from each physical zone or layer that is within the bulk of the membrane through which the ultrasonic energy has passed changes for each such zone.

Detailed Description Text (26):
In applying the present invention to a particular type of membrane module and to particular membrane fouling conditions, calibration or reference data are obtained in order to permit the characteristics of clean and fouled membrane surfaces to be distinguished, one from the other. In this way, the invention provides a measure of the presence or absence of membrane fouling.

Detailed Description Text (29):
A fouling meter in accordance with this invention includes one, or more, ultrasonic transducers and a comparison means (see FIG. 15 for example), or a signal processing means, that, when calibrated to a clean membrane standard, provides an output of a membrane fouling/cleaning condition. Such an output may be based upon a number scale that extends from 1 to 10, wherein increasing numbers correspond from clean to fouled for a particular membrane module system.

Detailed Description Text (46):
In either event, when a time-domain comparison threshold and/or amplitude domain comparison threshold, and/or frequency domain comparison threshold that is provided by network 86 is met relative to signals 85 and 76, an output 88 is provided, indicating that the membrane module that is being used to process a liquid is beginning to foul and should be cleaned, or indication that a membrane module that is being cleaned has been sufficiently cleaned, whereupon the costly cleaning process is terminated. In addition, if desired, a digital oscilloscope 89 may be added to enable visual inspection of the sensing output 90 of pulser/receiver 87.

Detailed Description Text (65):
In a simple multiple scattering system, the log decrement that is obtained from the processed time-domain signal changes as a function of membrane fouling. The magnitude and the separation of peaks in the frequency-domain (spectrum) change for multiple layers, as the layers foul.

CLAIMS:

14. A met hod of monitoring a state of fouling of membranes in a multi-layer

configuration, comprising the steps of:

providing a membrane module having a housing with an outer surface, having said multi-layer membrane configuration contained within said housing, having a feed inlet, having a permeate outlet, and having a retentate outlet;

providing a first and a second ultrasonic transducer, each of said transducers having a face surface that generally corresponds to said outer surface of said housing;

positioning said first transducer on said outer surface of said housing general adjacent to said feed inlet and with said face surface in physical engagement with said outer surface;

positioning said second transducer on said outer surface of said housing general adjacent to said retentate outlet and with said face surface in physical engagement with said outer surface;

pulse energizing said first and second transducers;

detecting a first and a second membrane echo signal that are respectively produced by said pulse energization of said first and second transducers;

said first membrane echo signal being indicative of membrane fouling generally adjacent to said feed inlet;

said second membrane echo signal being indicative of membrane fouling generally adjacent to said retentate outlet;

comparing said first membrane echo signal to said second membrane echo signal; and

determining said state of fouling of said multi-layer membrane configuration based upon said comparing step.

27. The apparatus of claim 24 wherein said housing comprises an elongated cylinder, with said liquid feed inlet being located generally at one end of said cylinder, and with said retentate outlet being located generally at an opposite end of said cylinder, said apparatus including:

a plurality of sensing ultrasonic transducers mounted at a plurality of spaced positions along a length of said cylinder, said plurality of sensing transducers being periodically connected to said sensing pulser/receive means so as to provide for the periodic sensing of membrane fouling at membrane positions generally corresponding to said plurality of spaced positions.

30. The apparatus of claim 24 wherein said housing comprises an elongated cylinder with said liquid feed inlet being located generally at one end of said cylinder and with said retentate outlet being located generally at an opposite end of said cylinder, said apparatus including:

motor means operable to move said at least one transducer between spaced locations along a given length of said cylinder so as to provide for the sensing of membrane fouling along a membrane length generally corresponding to said given length of said cylinder.

37. The method of claim 33 wherein said housing comprises an elongated cylinder with said liquid feed inlet being located generally at one end of said cylinder and with said retentate outlet being located generally at an opposite end of said cylinder, said method including the step of:

providing a plurality of sensing ultrasonic transducers mounted on an outer surface of said cylinder and at a plurality of spaced positions along a length of said cylinder, said plurality of sensing transducers being connected to said sensing pulser/receive means so as to provide for the sensing of membrane fouling at membrane positions generally corresponding to said plurality of spaced positions.

40. The method of claim 33 wherein said housing comprises an elongated cylinder having said liquid feed inlet located generally at one end of said cylinder and having with said retentate outlet located generally at an opposite end of said cylinder, said method including the step of:

providing motor means operable to move said at least one sensing transducer between spaced locations along a given length of said cylinder so as to provide for the sensing of membrane fouling at a membrane length generally corresponding to said given length of said cylinder.

43. A method of determining a state of fouling of a polymeric membrane that is contained within a housing of a spiral-wound membrane module or a hollow fiber membrane module, comprising the steps of:

positioning a sensing ultrasonic transducer with an emitting/receiving face in physical engagement with an outer surface of said housing;

electrically connected said sensing transducer to an ultrasonic pulser/receiver device;

pulse energizing said sensing transducer by operation of a pulser portion of the pulser/receiver device;

detecting a membrane echo signal by operation of a receiver portion of said pulser/receiver device;

providing a reference echo signal that is indicative of an predetermined state of membrane fouling; and

determining a state of fouling of said membrane based upon a comparison of said membrane echo signal to said reference echo signal.